



Electron Clouds in the Relativistic Heavy Ion Collider

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PART I: INTRODUCTION

1. BNL and the Relativistic Heavy Ion Collider
2. Electron Cloud build-up mechanism
3. Electron Clouds in RHIC? – Goals of the thesis

PART II: EXPERIMENTAL OBSERVATIONS

PART III: MAPS FOR ELECTRON CLOUDS

PART I: INTRODUCTION

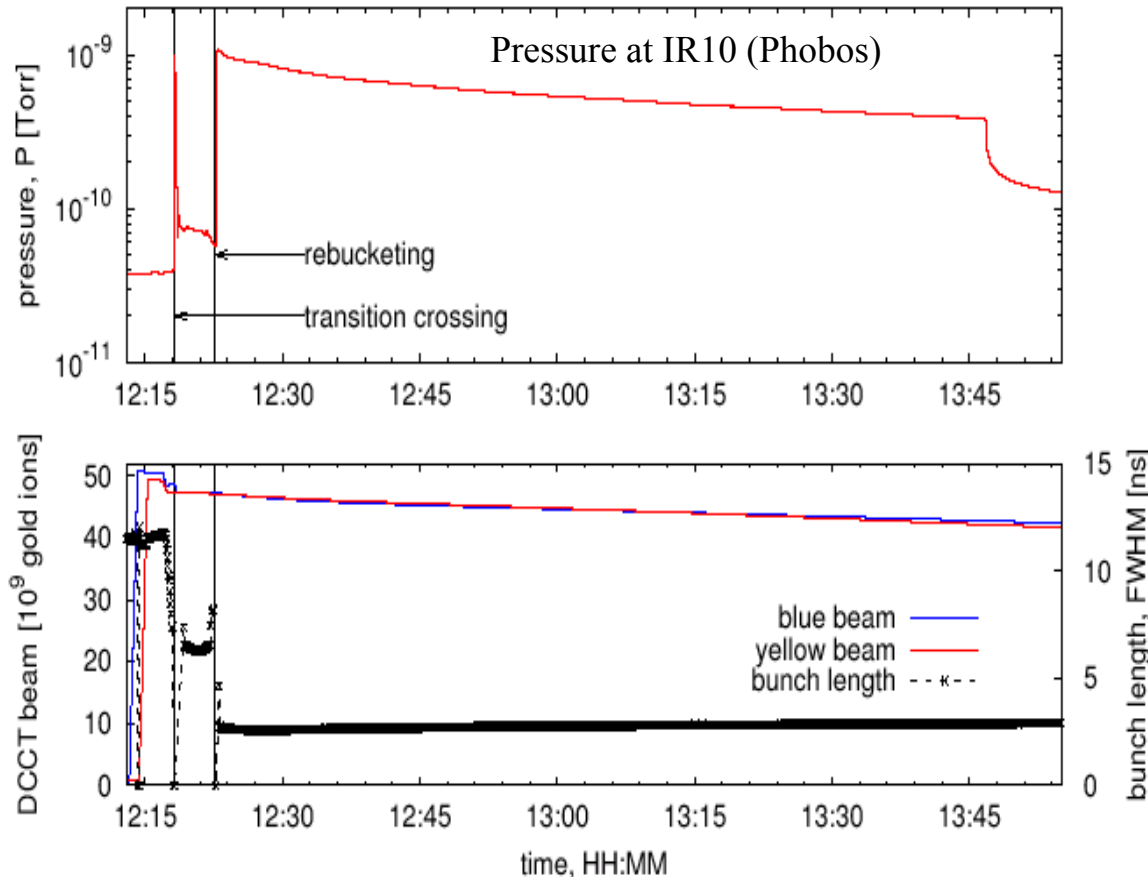
PART II: EXPERIMENTAL OBSERVATIONS

4. The RHIC electron detector
5. Electron induced molecular desorption in RHIC
6. Electron clouds during beam injection: benchmarking
experimental data with computer simulation codes
7. Pressure rise in the Interaction Regions
8. Possible remedies

PART III: MAPS FOR ELECTRON CLOUDS

7. Electron clouds in the Interaction Regions

- Questions after analysis in 2002: can beam losses induce pressure rises?

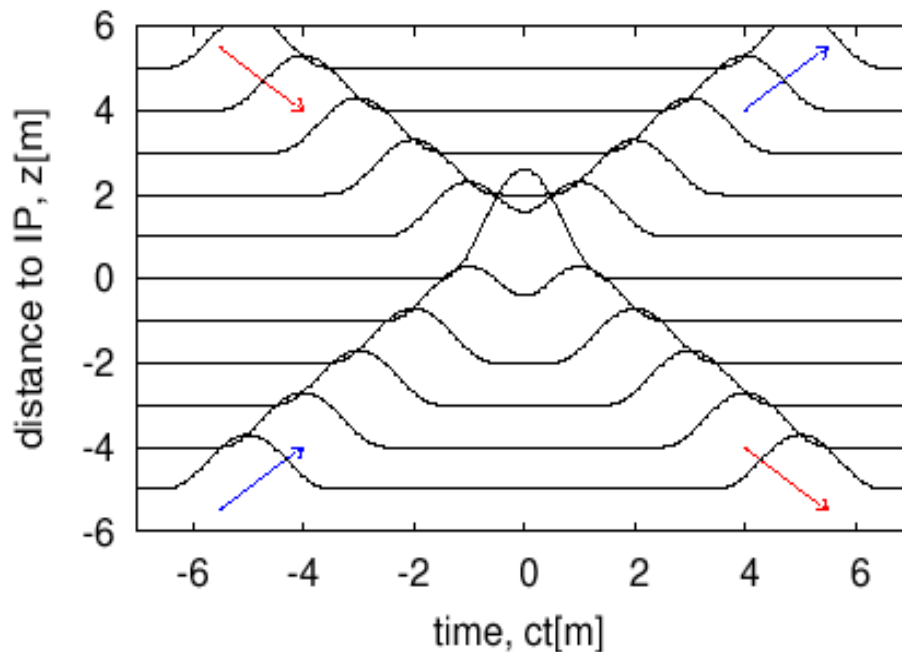


- Physics fills (for the users) use beam conditions that avoid e-clouds at injection.
- But pressure rises appear, mainly at IR, during “transition” and “rebucketing”, when some beam losses occur and as the bunch length shrinks.

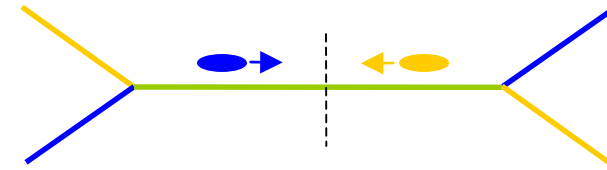


- *Is this due to beam losses?*

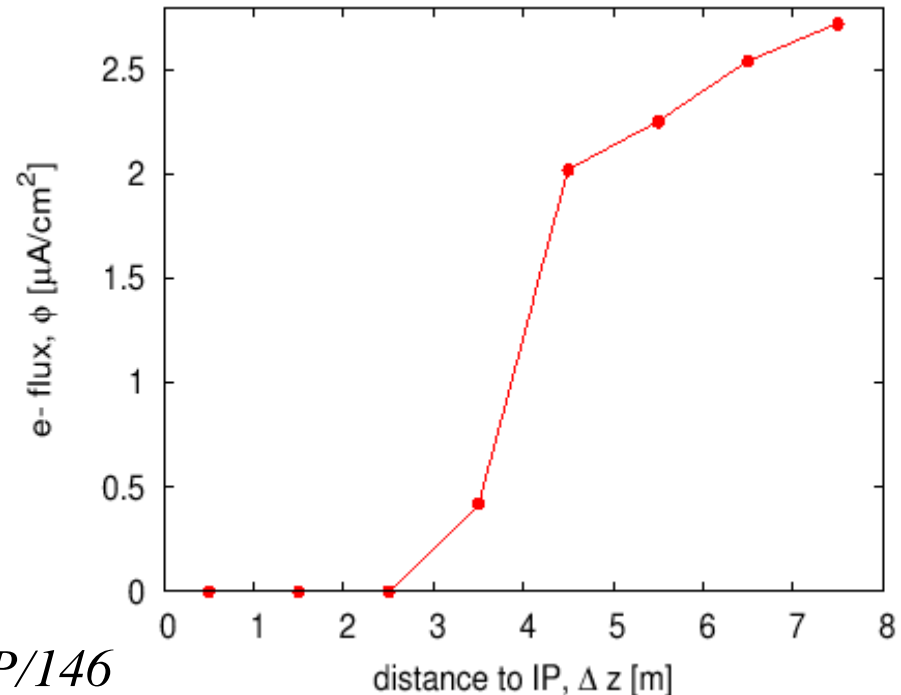
e-cloud effects when two beams cross the same chamber



→ e-clouds depend on the longitudinal position (consistent with Ref.*)



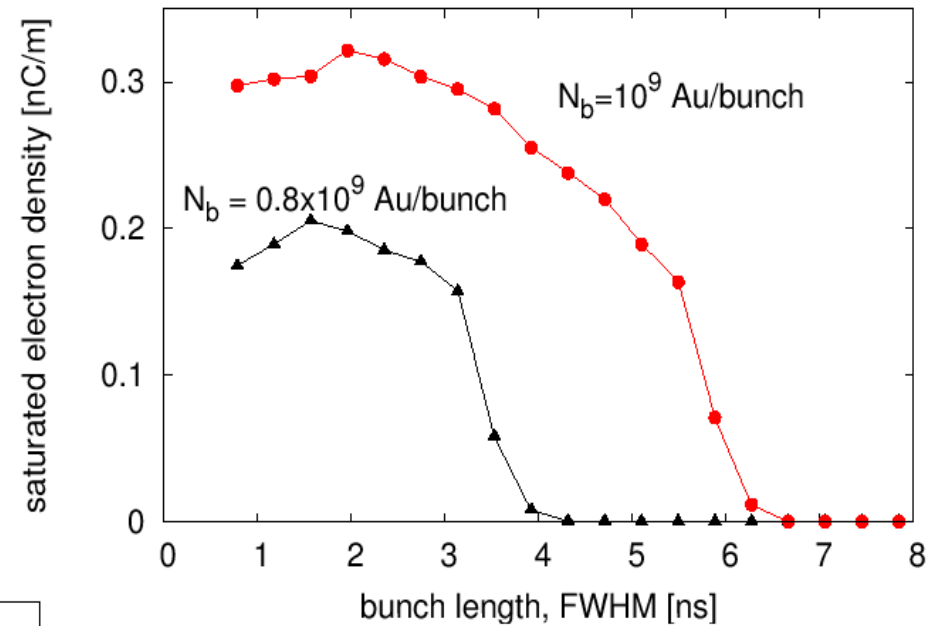
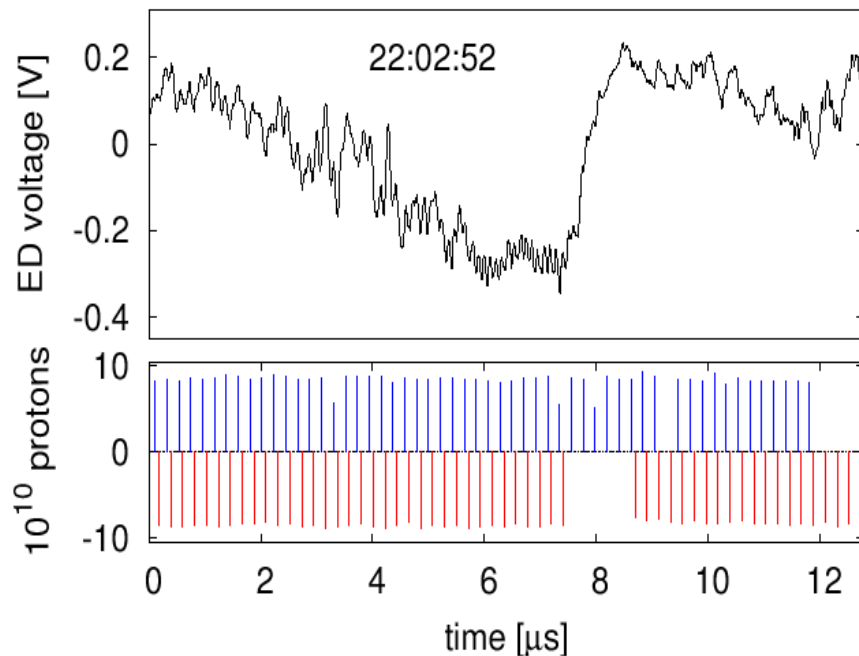
→ The combination of the blue and yellow bunches in a common beam pipe creates shorter bunch spacings
→ Different bunch profiles
→ Larger bunch intensities.



*G. Rumolo and W. Fischer, CAD/AP/146

Bunch length influence

CSEC simulations for PHOBOS
at $\Delta z = 7\text{m}$ \rightarrow *e*-clouds trigger
when bunch shrinks (consistent
with transition and rebucketing)



An experimental evidence: ED at IR12

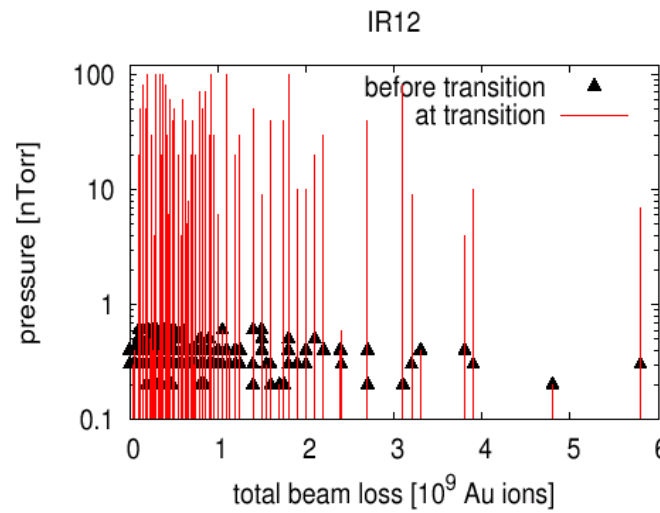
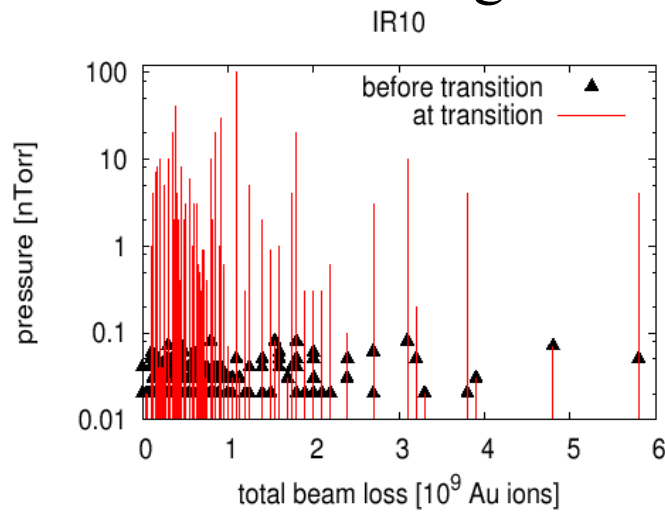
\rightarrow No multipacting in presence of only one beam (blue)

\rightarrow Injection of the Yellow beam leads to *e*-clouds

\rightarrow Multipacting decays in absence of one of the beams, but with a large decay time:

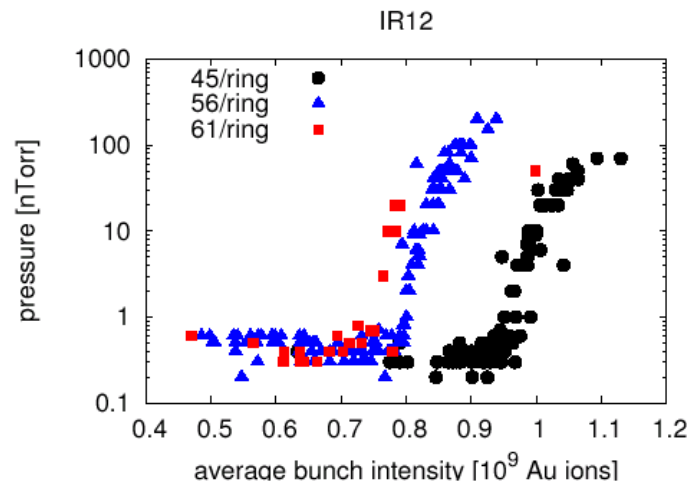
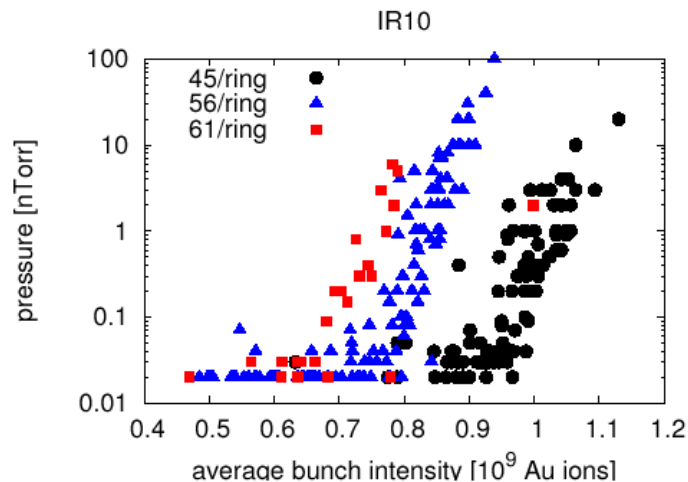
Statistics for IR10 and IR12

Data taken during Run 4 when the beams crossed the transition energy



Pressure vs Beam loss

No relation between beam losses and pressure rises at transition



Pressure vs avg. bunch intensity

Bunch intensity threshold decreases when the bunch spacing decreases (i.e., larger # of bunches)

➔ Observations and simulations conclude pressure rises at IRs are consistent with electron clouds

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PART II: EXPERIMENTAL OBSERVATIONS

PART III: MAPS FOR ELECTRON CLOUDS

9. Maps for Electron Clouds

10. The linear map coefficient

11. Coupled maps for electron and ion clouds

9. Maps for Electron Clouds

9.1. Motivation:

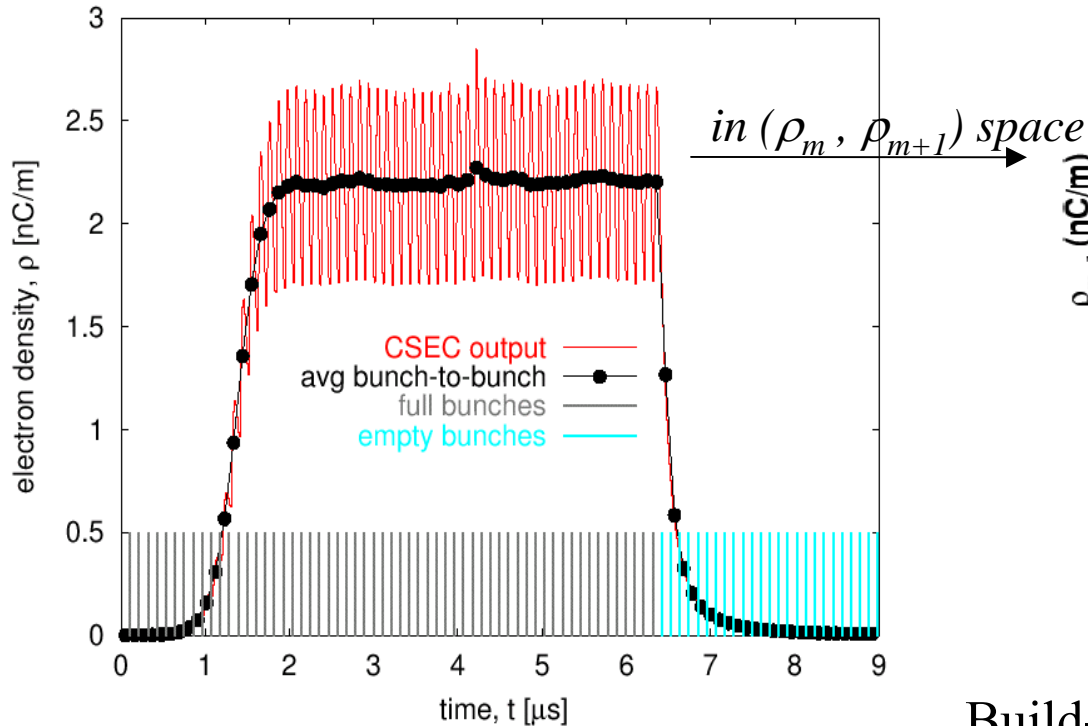
- At each time step ($\sim 1\text{ns}$ to $\sim 10\text{ns}$), the necessary forces and fields are computed to track the electron (or “macroelectron”) motion (*CSEC*, *ECLLOUD*, *POSINST*, *CLOUDLAND*, ...)
- Results strongly depend on the input parameters (only for the SEY, there are more than 8 parameters).
 - ➔ simulations need large CPU time: between 1hour or 1 week
- Is there any other approach to treat electron clouds in a simpler way?

For a given chamber, e-cloud depends on bunch characteristics

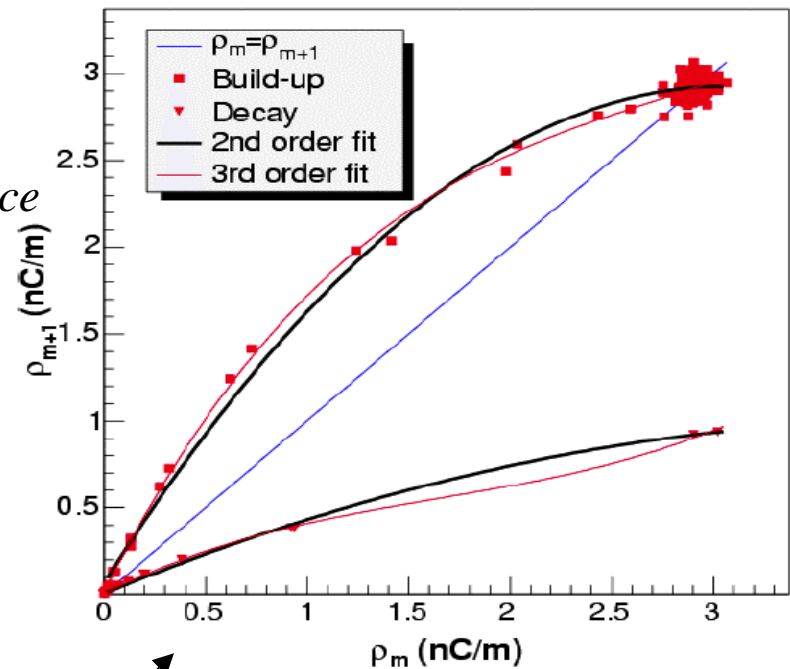
Natural time step: the *bunch passage*.

Proposal: follow the e-density ρ in a *bunch to bunch* evolution, using iterative formalisms.

$$\longrightarrow \boxed{\rho_{m+1} = f(\rho_m)}$$

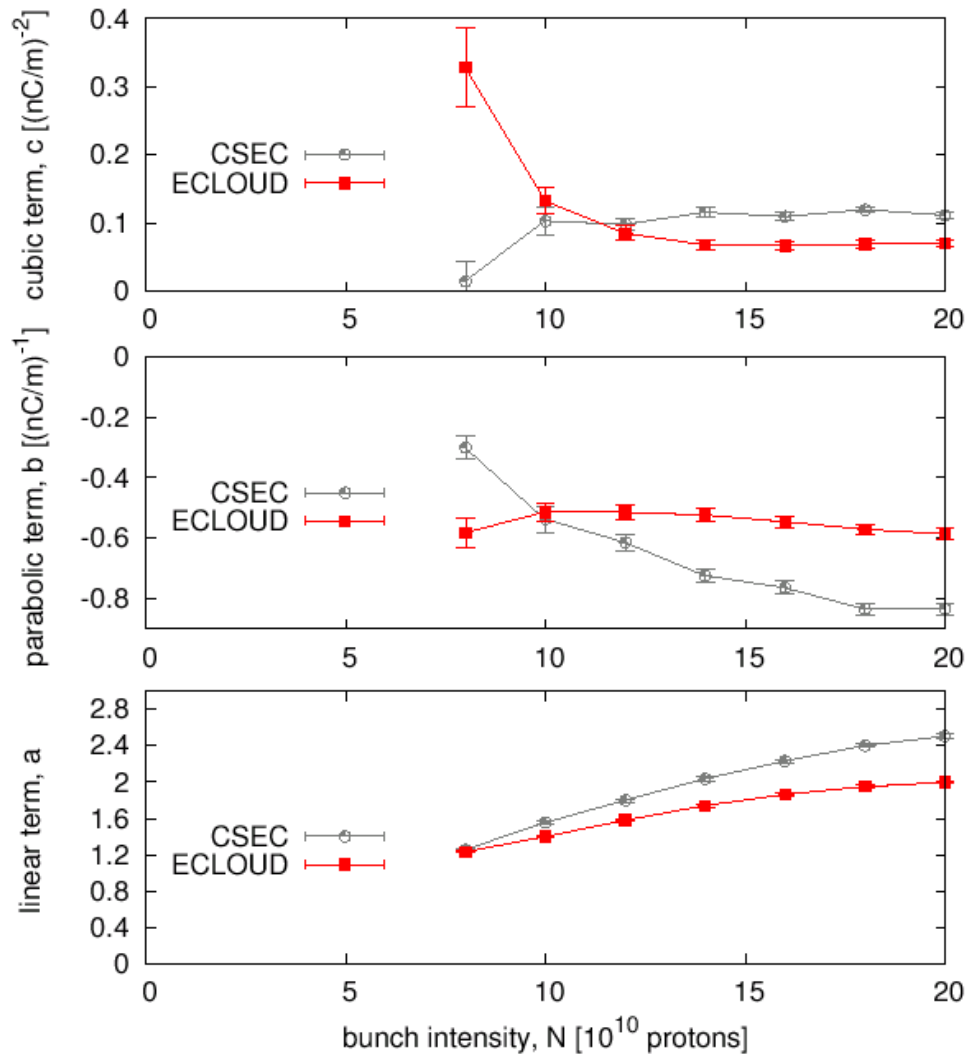


Growing $N=20 \times 10^{10}$ ppb, Decaying $N=00 \times 10^{10}$ ppb



Build-up evolution close to a parabola, getting to saturation at the “identity map”, the 45° line.

Empirical determination of $\vec{a}(N_m)$ using *CSEC* and *ECLOUD*



$\vec{a} = \begin{cases} a(N) & \rightarrow \text{linear term} \\ b(N) & \rightarrow \text{parabolic term} \\ c(N) & \rightarrow \text{cubic term} \end{cases}$

Once we have $\vec{a}(N_m)$, we just need an algorithm depending on N_m , being m the bunch number in the bunch train

Much faster than following ρ ns-to-ns using contemporary e-cloud simulation codes ($\sim 1h$ vs $\sim 1ms$)

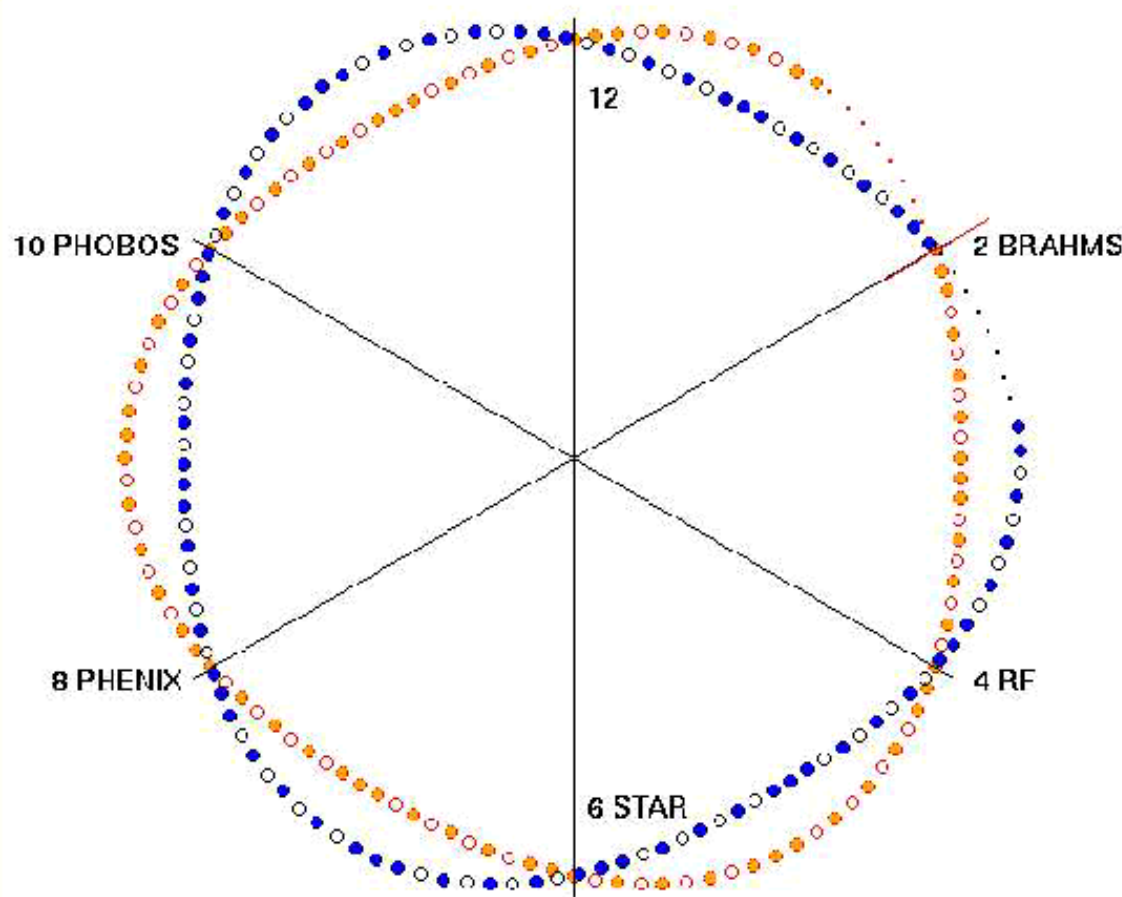
Unfortunately, we still need *CSEC* or *ECLOUD* to obtain the vector $\vec{a}(N)$..

But it is still very useful...

9.2. A maps application to RHIC

QUESTION:

For a given number of bunches, M , in a train of H possible bunches, what is the best way to place the M bunches?



Example: $M=68$ bunches in $H=110$ possible places

$$\frac{110!}{(110 - 68)!68!} \approx 10^{30}$$

Using *CSEC* or *ECLLOUD*, each case takes $\sim 1\text{h}$...

Much faster ($\sim 1\text{ms}$) using Maps for Electron Clouds: *MEC*

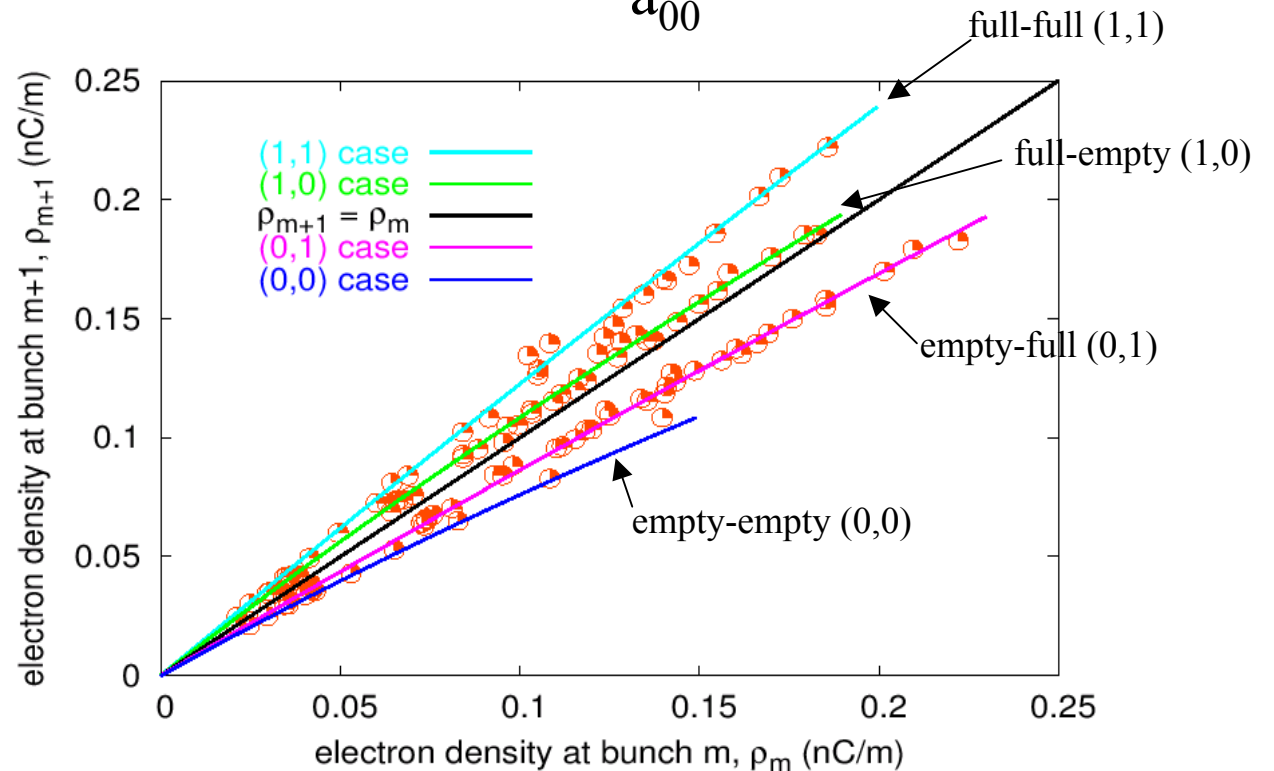
Answer 1: using the fast code, MEC

With non-uniform bunch patterns, it is heuristically found that a complete e-cloud build-up and decay needs actually four 3-vectors, depending on bunch m and bunch $m-1$

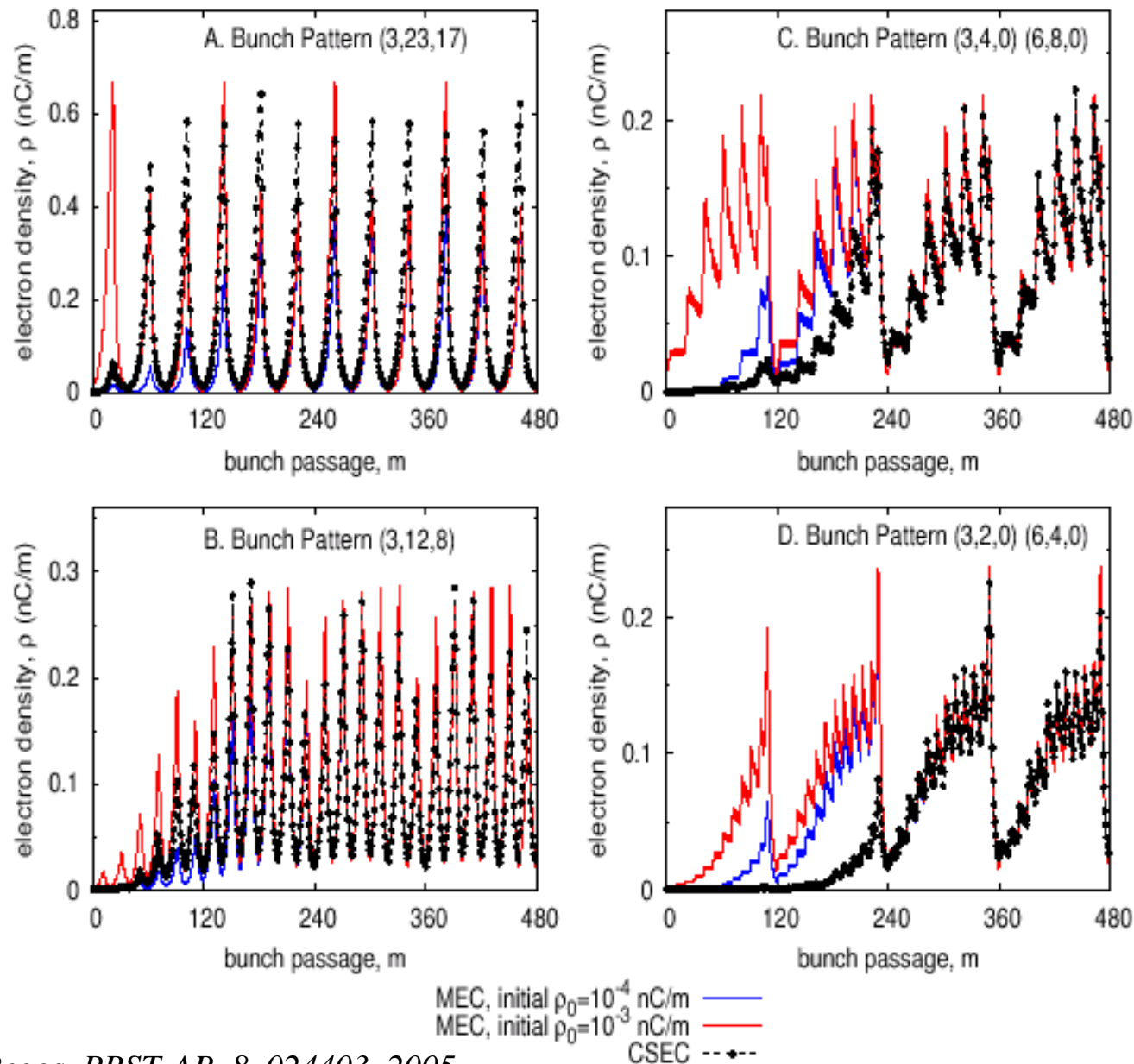
<i>bunch m</i>	<i>bunch m-1</i>
Full	Full
Full	Empty
Empty	Full
Empty	Empty

➤ a_{11}
➤ a_{10}
➤ a_{01}
➤ a_{00}

This is because ρ “jumps” from the curve full-full (1,1) to empty-empty (0,0) in two bunch passages.



- Computer program including the 4 vectors, **MEC** (Maps for Electron Clouds)
- Good agreement vs **CSEC** results with different bunch patterns*



*U. Iriso and S. Peggs, *PRST-AB*, 8, 024403, 2005

Answer 2: mathematical analysis

H : possible buckets to fill in one turn

M : bunches to distribute around the circumference

i : transitions (full-to-empty, and vice versa)

→ Linear approximation for small ρ $\rho_{m+H} = F(N) \cdot \rho_0$

For a given **M**, a minimum **F** requires $\rightarrow \left[\frac{a_{10} a_{01}}{a_{11} a_{00}} \right]^i < 1 \rightarrow$ large values of **i** !!

Large values of **i** → large number of transitions → most sparse distribution!!

→ Current way to distribute bunches at RHIC to minimize e-clouds

→ This is why the RHIC injection program was upgraded

• *MEC speeds up of simulations by ~7 orders of magnitude compared with contemporary simulation codes.*

• *This way of tackling e-cloud renders conclusions, which would otherwise difficult to obtain.*

10. The linear map coefficient

Map coefficients are inferred by fitting results obtained running long computer simulations codes, *CSEC* or *ECLOUD*.

With some assumptions, this Chapter shows how to calculate the linear map coefficient *a* using first principles.

Assumptions about e- motion:

e- only travel in the transverse plane, in the radial direction: $\text{TOF} = 2b/v_{e-}$

Assumptions about e- multiplication:

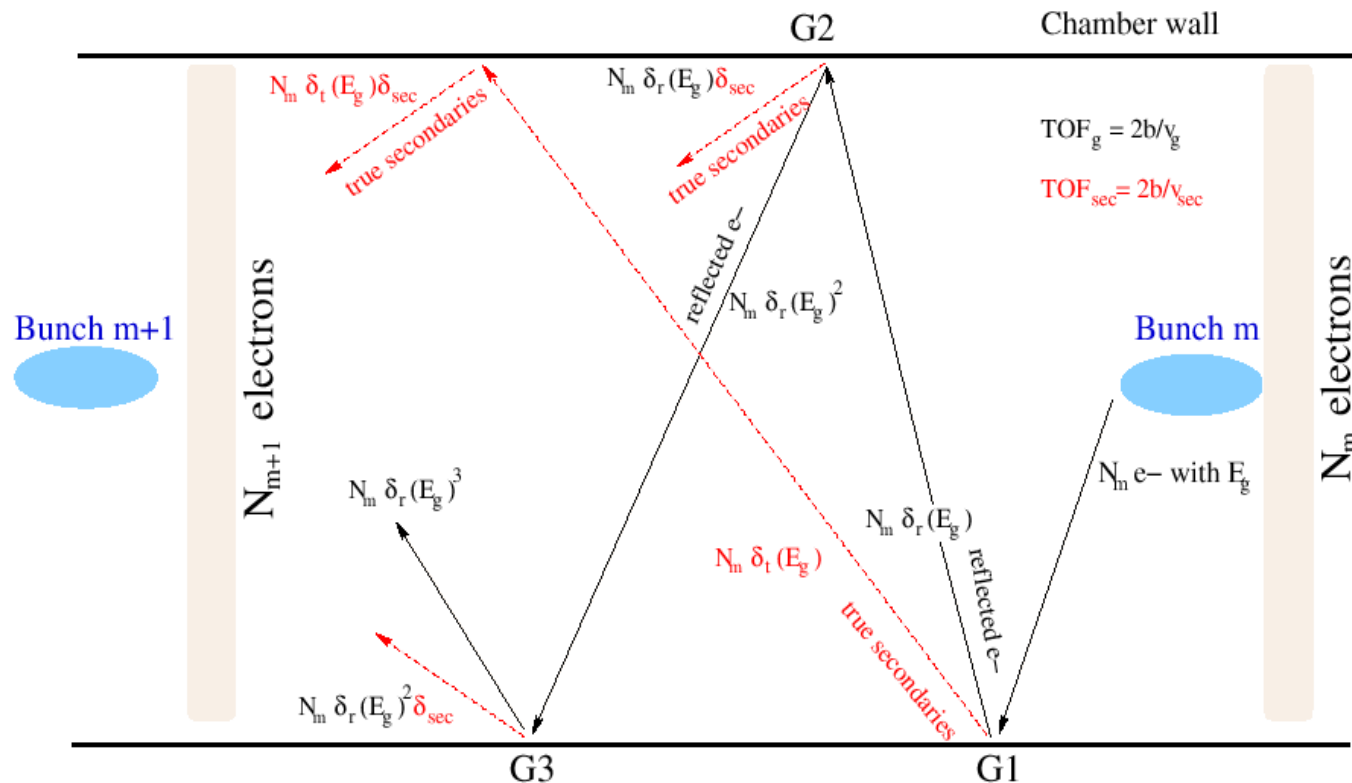
After an electron-wall collision, secondaries are emitted at

- low energy (5 eV)
- same impinging energy (backscattering)

rediffused electrons are neglected

- Method:**
0. Assume N_m electrons uniformly distributed in the beam pipe
 1. Evaluate electron energy gain during bunch passage (e-bunch interaction)
 2. Compute multiplication at the wall collision using the SEY, i.e. $\delta(E)$
 3. Calculate how many electrons survive before next bunch passage, N_{m+1}

Linear map coefficient $\Rightarrow a = N_{m+1} / N_m$



Adding up all contributions, that is,

- electrons surviving after low energy wall collisions (at $\sim 5\text{eV}$)
- electrons surviving after high energy wall collisions

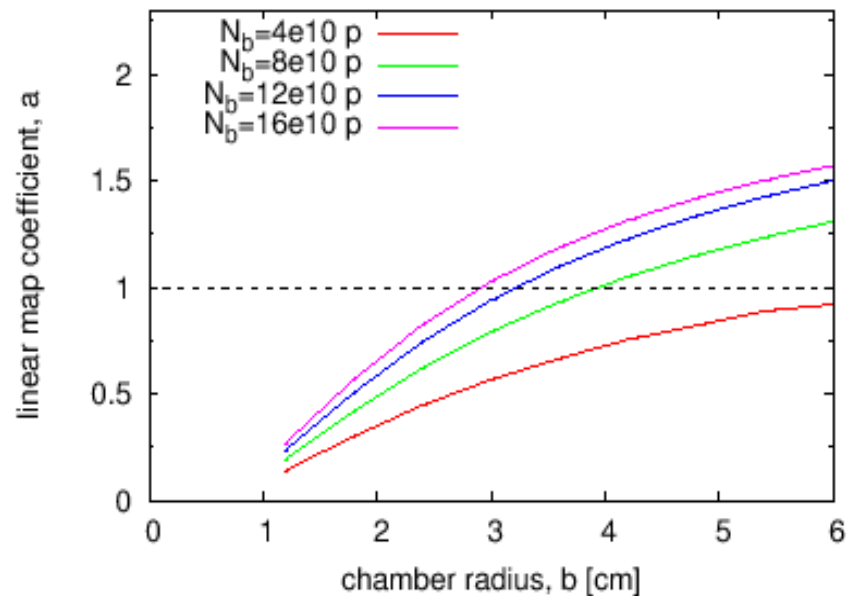
$$a = \int_0^\infty \left[\delta_r(E)^{n(E)} + \delta_t(E) \delta_{\text{sec}}^{\xi(E)} \frac{\delta_{\text{sec}}^{n(E)\xi(E)} - \delta_r^{n(E)}}{\delta_{\text{sec}}^{\xi(E)} - \delta_r(E)} \right] h(E) dE$$

$h(E)$ is the electron energy spectrum after bunch passage (Berg's formula)

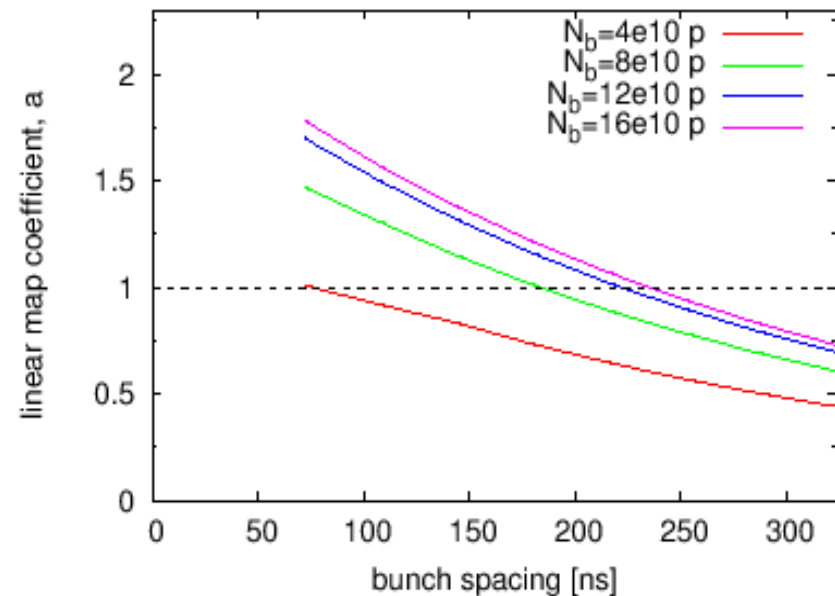
Linear Map Coefficient = effective SEY (δ_{eff}) of the beam pipe, because it takes into account surface chamber properties, bunch characteristics, and bunch spacing.

→ Since $a > 1$ marks the threshold for an electron cloud formation, this results in an easy way to explore parameter space and obtain safety regions for machine operation

Example for beam pipe radius

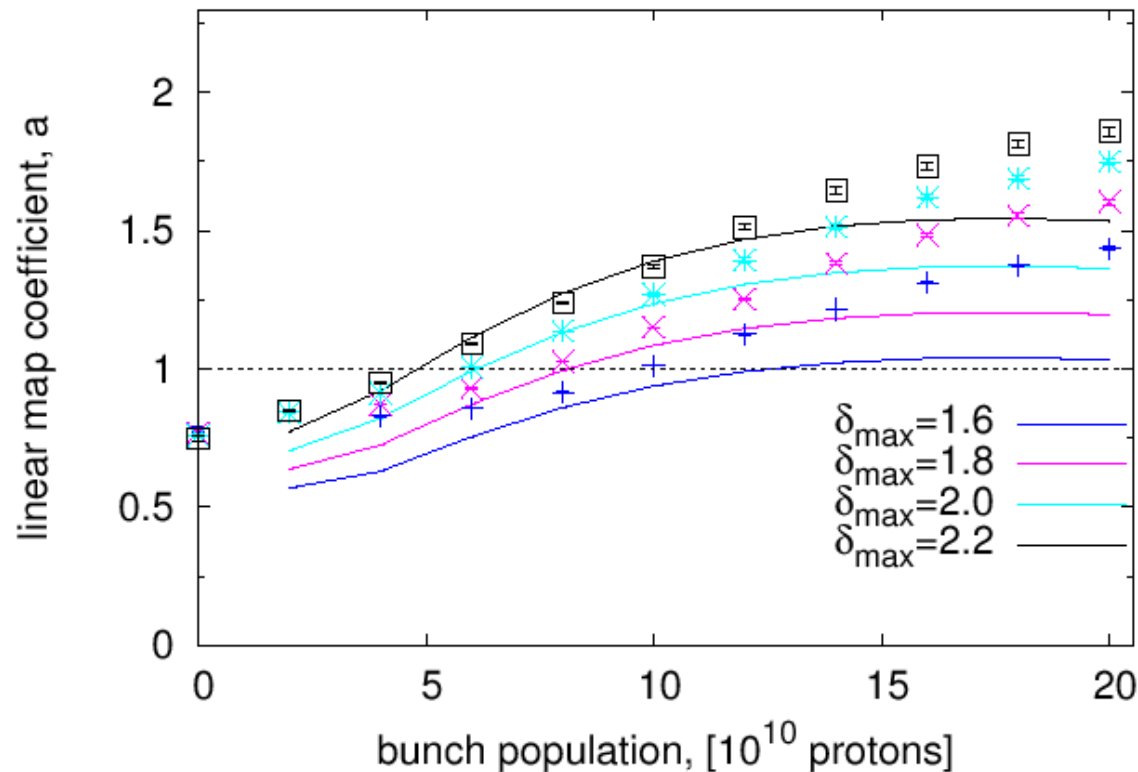


Example for bunch spacing



Comparison with simulation results

Results scanning the bunch population and for different δ_{\max}



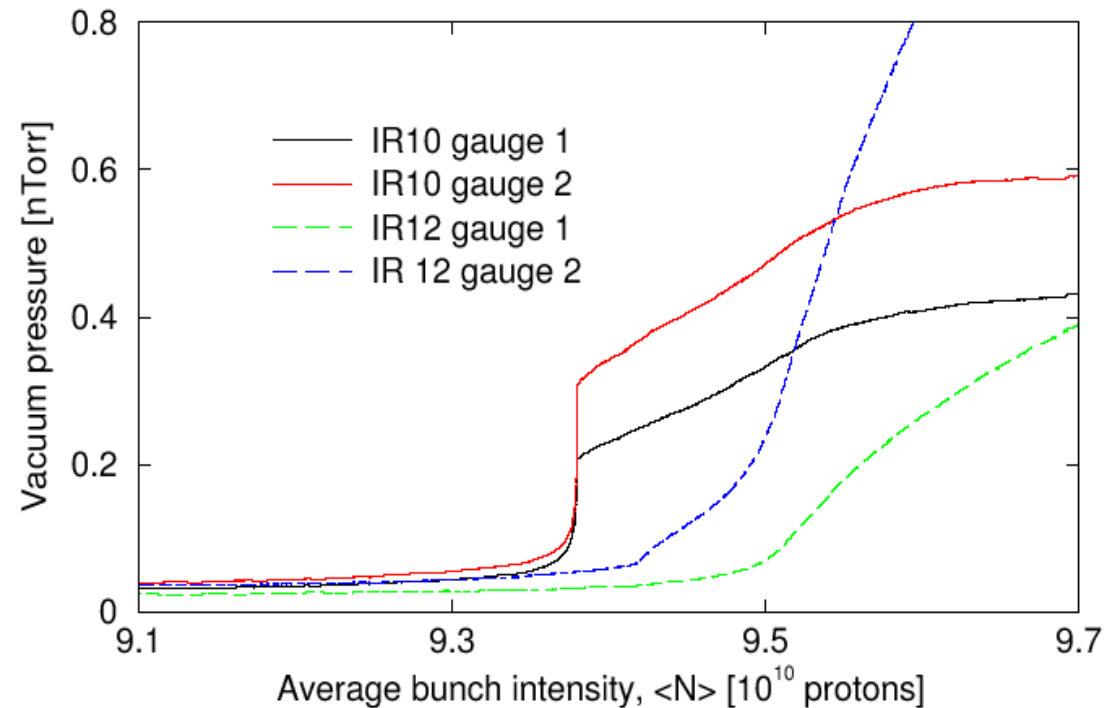
Points \rightarrow **CSEC** results

Lines \rightarrow Analytical results

- Acceptable agreement around the threshold, $a \sim 1$
- Disagreement mainly due to neglecting the contribution of the rediffused electrons: the model fails for large energy gains, i.e. for large bunch intensities

11. Maps for coupled electron and ion clouds

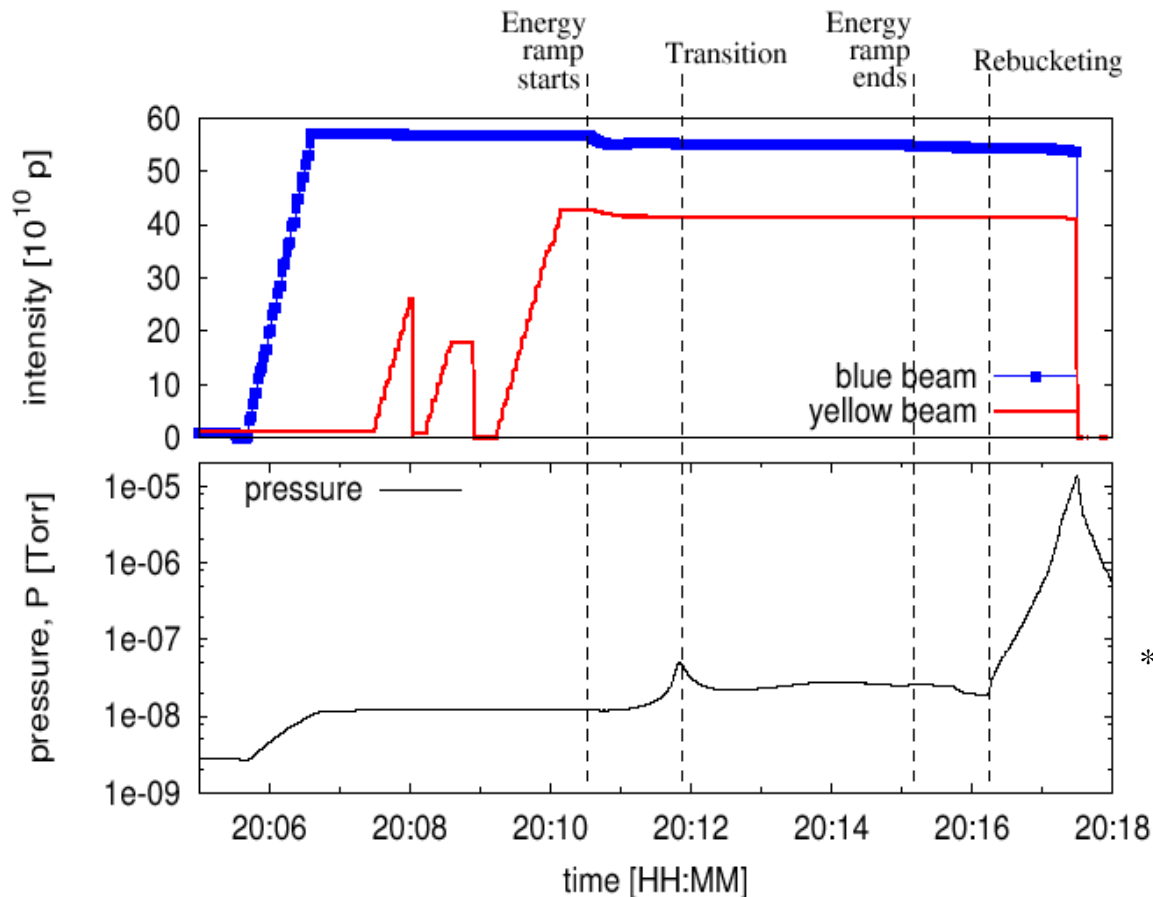
11.1. First and second order phase transitions



- Pressure (due to e-clouds) smoothly decays in IR12, it shows an abrupt decay in IR10, as the bunch intensity threshold for e-clouds is crossed.
- But contemporary simulation codes only reproduce a smooth transition from “off” \leftrightarrow “on” *
- How can both first and second order phase transition occur in e-clouds?

*S. Peggs and U. Iriso, *Proceedings of ECLLOUD'04*, 2004

11.2. A vacuum instability driven by e-clouds



Proposed explanation*:
e-clouds and beam-gas
collisions create ions, leading
to a vacuum instability

*W. Fischer, U. Iriso, E. Mustafin, CARE-HHH,
ICFA 2004

- Ion lifetime can be ~3-6 orders of magnitude larger than electrons
 - Significant number of parameters to determine ion creation and motion:
ionization cross sections for different gases, backscattering probability, vacuum pumping, etc
- Rather complex to be introduced into **CSEC** (prohibitively large CPU times)

→ Maps can circumvent this prohibition

11.3. Iterative coupled maps for electron and ion clouds

Assume ion clouds can be formed and “couple” them to the electron cloud using maps:

$$\begin{aligned}\rho_{m+1} &= f(\rho_m, R_m) \longrightarrow \text{for electron density} \\ R_{m+1} &= g(\rho_m, R_m) \longrightarrow \text{for ion density}\end{aligned}$$

The 2-system is characterized by the vector $\vec{r}_m = \begin{pmatrix} \rho_m \\ R_m \end{pmatrix}$

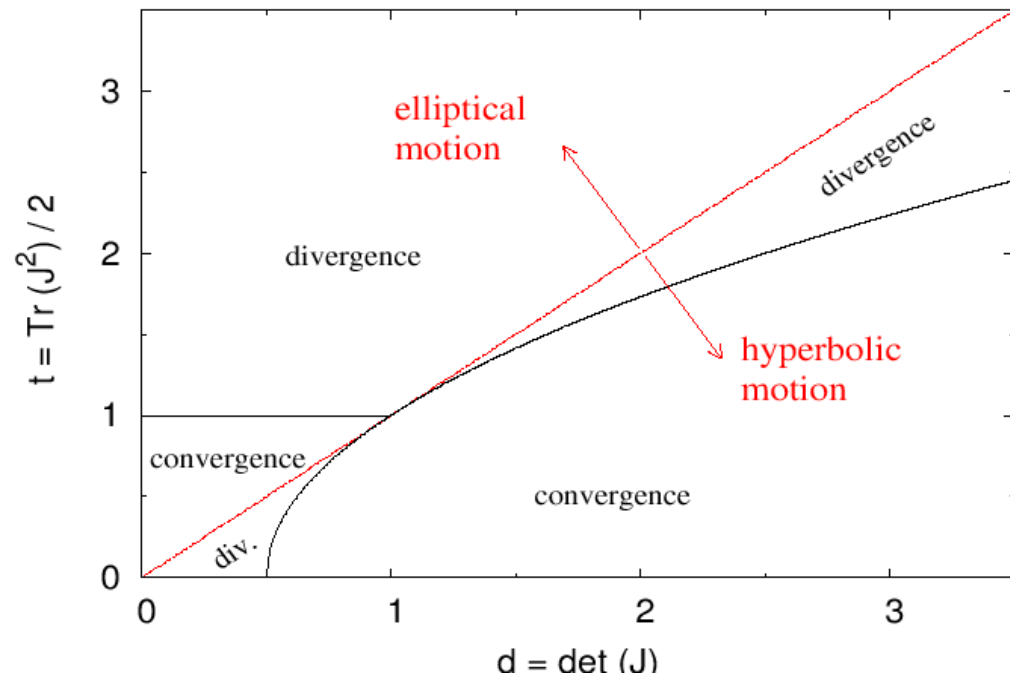
Equilibrium is found if $\vec{r}_{m+1} = \vec{r}_m \equiv \vec{r}^*$ at the so-called, “fixed points”

➔ But we need the fixed points to be *stable*!!

- Stability condition of the fixed points depend on the Jacobian matrix:

$$J = \begin{pmatrix} \frac{\partial f}{\partial \rho_m} & \frac{\partial f}{\partial R_m} \\ \frac{\partial g}{\partial \rho_m} & \frac{\partial g}{\partial R_m} \end{pmatrix}_{\vec{r}^*}$$

**see Appendix D*



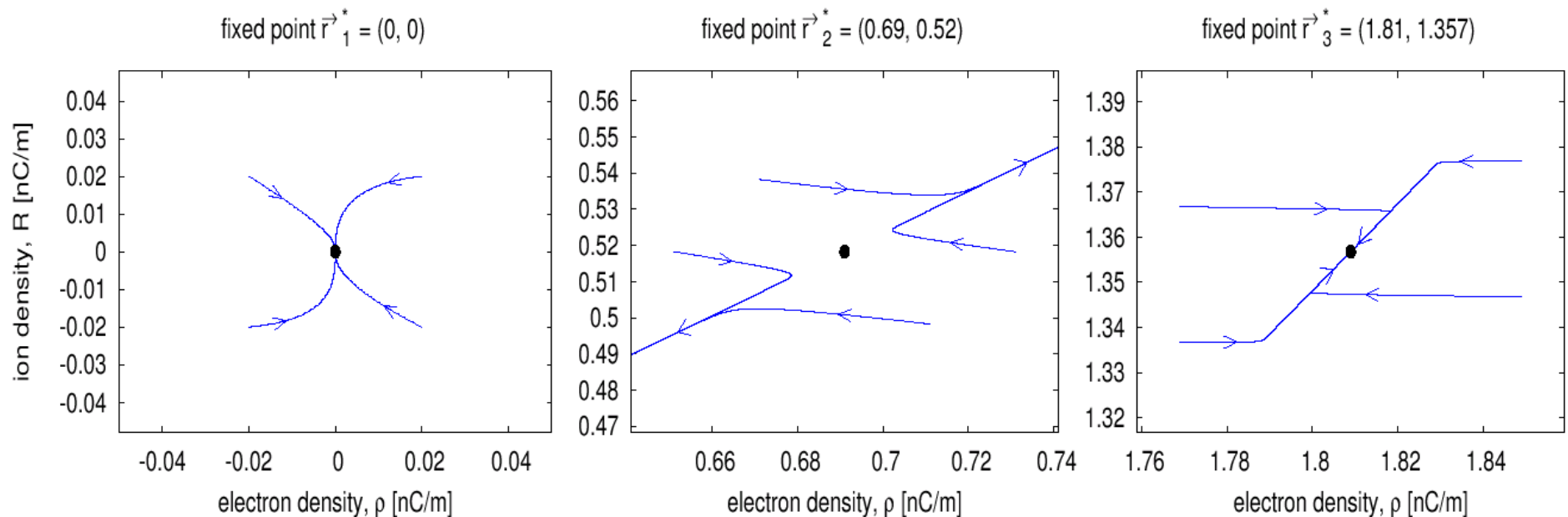
11.4. A coupled maps example model

$$\begin{aligned}\rho_{m+1} &= (a + b\rho_m + yR_m)\rho_m + c\rho_m^3 \\ R_{m+1} &= AR_m + Y\rho_m\end{aligned}$$

→ For a given bunch population **N**, more than one solution can be found.

→ For example (see text) 3-solutions are found for $N=5 \cdot 10^{10}$ protons/bunch:

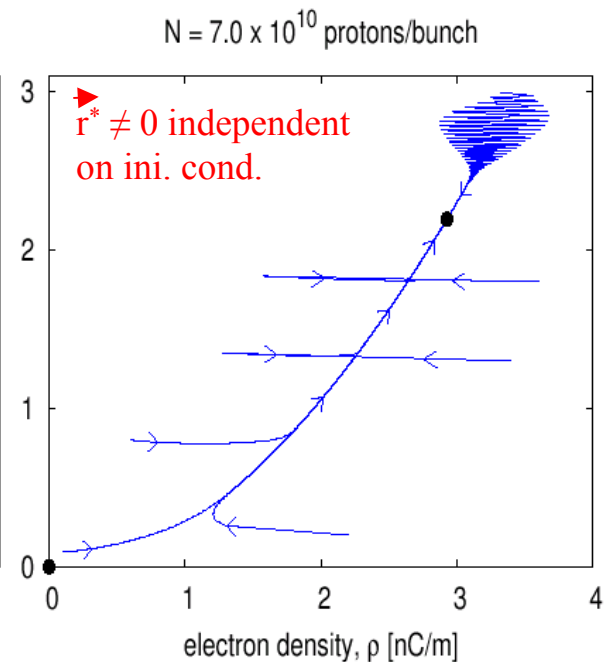
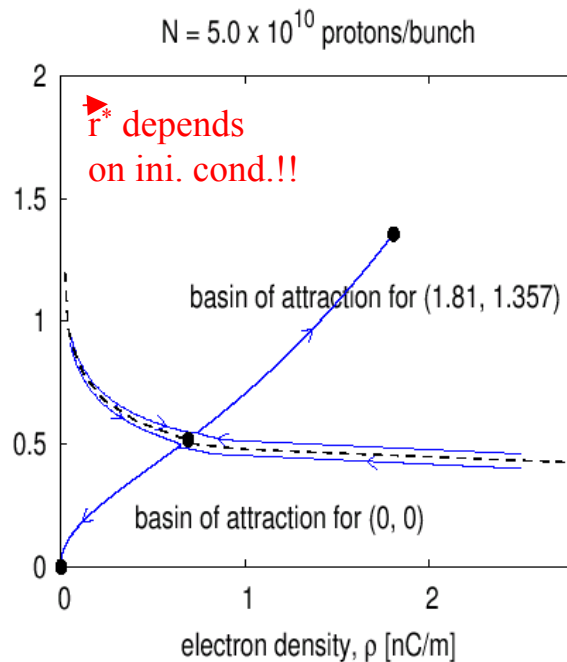
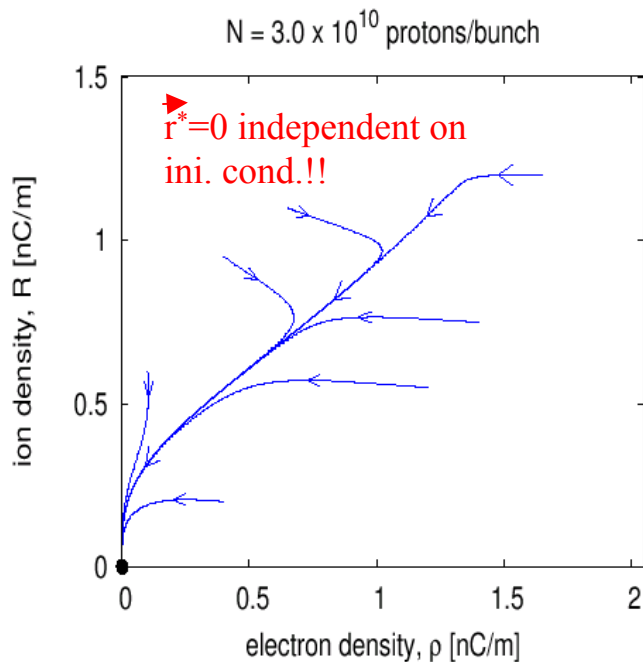
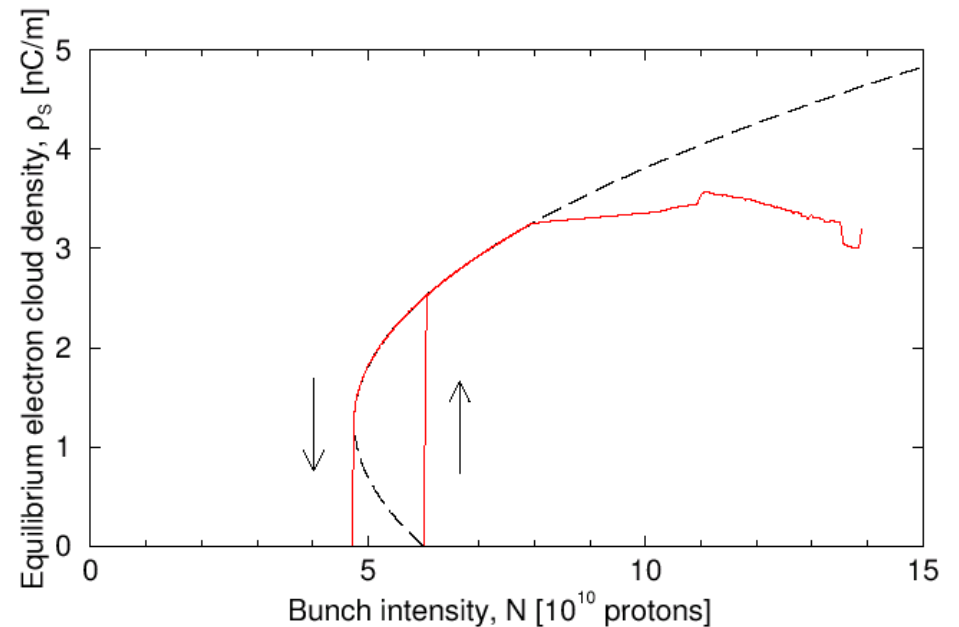
$$\left\{ \begin{array}{l} \vec{r}_1^* = (0, 0) \\ \vec{r}_2^* = (0.69, 0.52) \\ \vec{r}_3^* = (1.81, 1.35) \end{array} \right. \dots \text{and analyzing the Jacobian matrix...} \left\{ \begin{array}{l} \vec{r}_1^* \rightarrow \text{Stable fixed point} \\ \vec{r}_2^* \rightarrow \text{Unstable fixed point} \\ \vec{r}_3^* \rightarrow \text{Stable fixed point} \end{array} \right.$$



11.5. First order phase transition and hysteresis

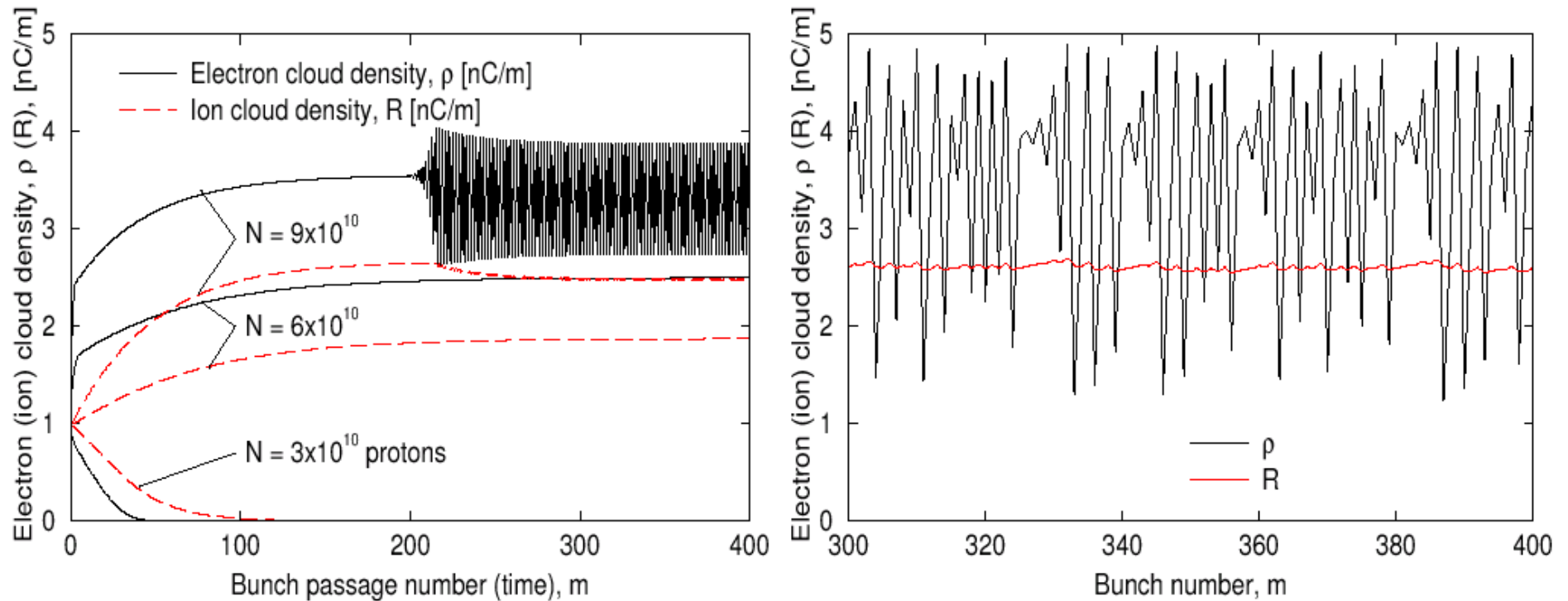
Results from a dynamical simulation based on the coupled maps first as N is slowly increased, then as N is slowly decreased

Hysteresis is observed because the final state depends on the initial conditions for some bunch intensities.



11.6. Additional dynamical phases

...and on top of it, chaotic regimes can be found...



- *Maps are really suitable to overcome CPU limitations presented by possible electron and ion clouds coupling.*
- *Development of stability conditions and a numerical example show electron clouds can show first order phase transitions, hysteresis, and additional dynamical phases.*

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CONCLUSIONS

Conclusions (1)

1. Electron detectors have been developed and successfully installed at RHIC, and they are permanently used to monitor electron cloud activity
1. This detector allowed to measure the desorption coefficient from electron impact
1. Electron energy spectrum during multipacting conditions has been measured for the first time at RHIC
4. Computer simulation codes have been benchmarked with experimental data to evaluate SEY parameterizations.

Conclusions (2)

1. A new model is presented to study electron clouds. The use of bunch-to-bunch maps allows faster simulations, renders conclusions that would otherwise be difficult to obtain, and enhances the physical understanding.
6. Possible coupling between electron and ion clouds has been introduced using maps, showing that first order phase transitions, and hysteresis can be found. They also predict chaotic regimes may appear near machine operating conditions.